An Integrated Field Assessment of Groundwater Recharge

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Abstract: Groundwater recharge is often assumed to be uniform within a watershed owing to difficulties in quantifying its temporal and spatial variability. In this paper, fluctuations in soil moisture content at multiple depths in the unsaturated zone together with fluctuations in the water table are used to provide a record of the recharge process and a means to quantify and compare temporal and spatial recharge variability. Hourly measurements of soil moisture content and the elevation of the water table were collected at two sites, a clear cut and a coniferous forest site, within the Trout Lake basin of northern Wisconsin. The soil moisture and water table data were used together to assess the temporal and spatial variability in groundwater recharge from October 1999 to May 2001 and to identify the climatic (amount and timing of rainfall) and physical (vegetation and soil type) controls on the recharge process within this basin. Together, the two datasets allow for a holistic assessment of the recharge process from the ground surface through the unsaturated zone down to the water table.

Keywords: Groundwater recharge, soil moisture, water table fluctuation.

INTRODUCTION

Recharge, defined as the entry of water into the saturated zone, varies spatially and temporally as it depends on a wide variety of factors (e.g., vegetation, precipitation, topography, geology, and soil type), making it one of the most difficult, complex, and uncertain water budget components to quantify [1]. Accurate recharge estimates, including both spatial and temporal distribution, require an understanding of the recharge process and the associated climatic and watershed parameter controls. Good recharge estimates are typically a pre-requisite for effective groundwater resource assessment, management, and flow modeling.

There has been extensive research on recharge estimation at a variety of scales [2-4], including studies that assess spatial and temporal recharge variability [5-16]. Nevertheless, groundwater modelers, planners, and policy makers frequently use a single recharge value for an entire watershed calculated as an assumed fraction of the annual average precipitation or as determined by model calibration. Use of a single annual value may be inappropriate, depending on the application, and, consequently, may invalidate model results and predictions, particularly where small scale or detailed flow path delineation is required over time [8, 17].

Detailed field monitoring of the subsurface can provide valuable insights into the recharge process and a means to calculate spatial and temporal recharge variability. Rainfall timing, intensity, and quantity, as well as antecedent soil moisture conditions, properties of the soil and sediment, thickness of the unsaturated zone, and types of vegetation, all influence soil moisture content and the water table response. Consequently, soil moisture and water table measurements collectively constitute a record of the recharge process in areas where precipitation is the only source of recharge, as they provide a means to track the timing and spatial distribution of precipitation-induced recharge.

In this study, hourly field measurements of soil moisture content and water table elevation were collected at two sites, a clear cut (CLR) and a coniferous forest (CON) site, within the Trout Lake basin of northern Wisconsin (Fig. **1**). The two data sets were used together to look at the temporal and spatial variability of groundwater recharge from October 1999 to May 2001 and to identify climatic and physical controls on the recharge process within this basin.

FIELD SITE

The Trout Lake basin is a sparsely populated, glaciated terrain with rolling upland hills covered with a mixed temperate forest interspersed among kettle lakes (Fig. **1**). Glaciers scoured the Precambrian metamorphic and igneous bedrock surface and deposited 30 to 50 meters [18, 19] of unconsolidated sand and coarse glacial till. Vibracores, drill logs, slug testing, and Guelph permeameter studies [20] show that the unconsolidated sediments consist of homogeneous, fine to medium grained outwash sands with hydraulic conductivities of 8 - 12 m/day.

The basin is part of the Northern Highland-American Legion (NHAL) State Forest managed by the Wisconsin Department of Natural Resources (WDNR). The WDNR has cut and maintained portions of the watershed for timber sales since the NHAL was established in 1925. The USGS Water, Energy, and Biogeochemical Budgets (WEBB) program monitors soil water and gas chemistry as well as groundwater levels and chemistry at numerous sites within the Allequash sub-basin [21]. At a select number of the sites, the

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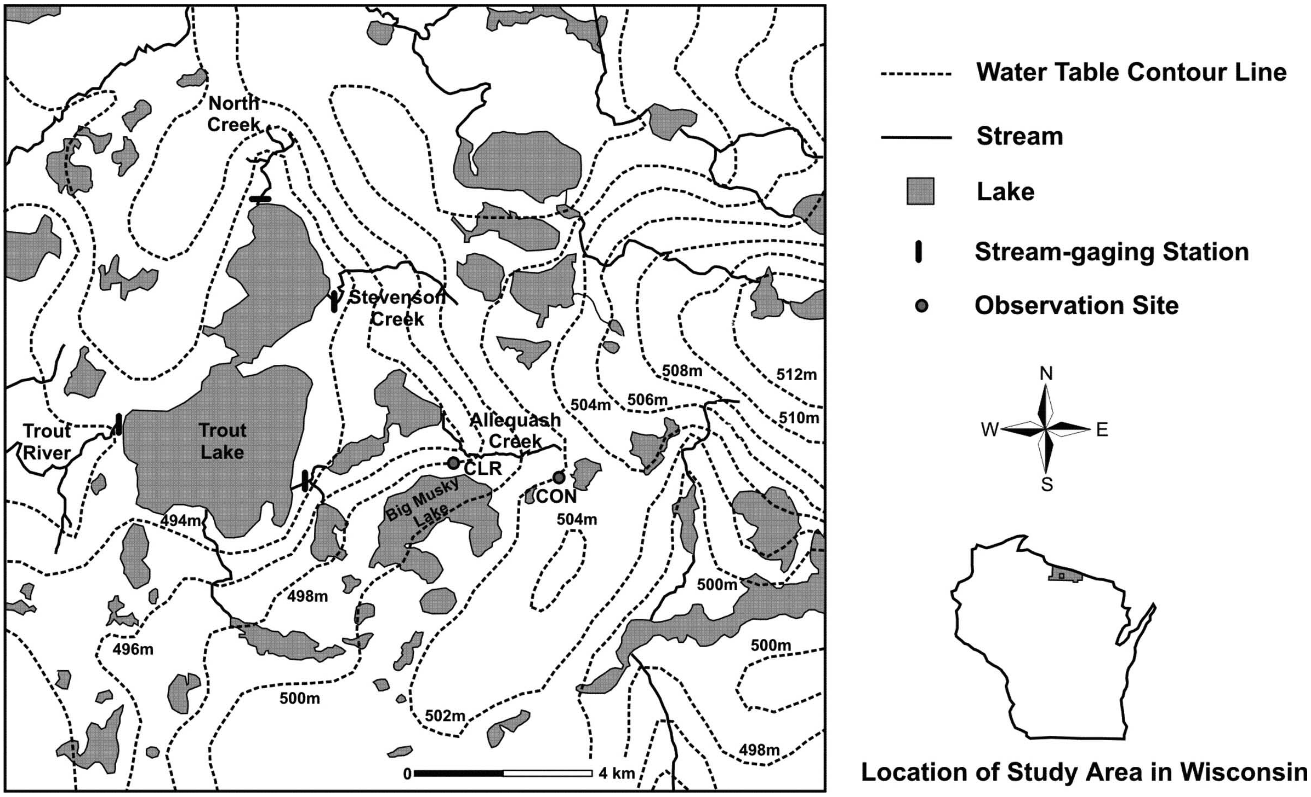

Fig. (1). Map of the Trout Lake study area in northern Wisconsin, showing elevation of the water table in meters above mean sea level and locations of the clear cut (CLR) and conifer (CON) study sites.

USGS maintains a three-meter deep soil pit from which sensors can be laterally inserted for data collection within the unsaturated zone.

METHODOLOGY AND DATA ANALYSIS

Soil Moisture Content

Three time domain reflectometers (CS615 Water Content Reflectometer, Campbell Scientific), which measure soil moisture, were installed in a clear cut and a coniferous forest soil pit (Fig. **1**) at depths of 0.25, 0.91, and 2.13 meters. At the conifer site, the upper two reflectometers were located within the root zone, but the deep reflectometer was just below the root zone.

A reflectometer consists of two parallel, stainless steel rods attached to a circuit board connected via a four-conducter cable to a CR10 datalogger, which supplies power, enables the probe, and records the sensor's output. Conversion of the reflectometer's output to a measure of the soil moisture content is based on a unique relationship between a soil's dielectric constant and its water content. The reflectometer measures the time it takes for an electromagnetic pulse to be transmitted between the two steel rods, once embedded in the soil. The travel time is dependent on the soil's dielectric constant, which is a function of the soil's moisture content.

Hourly soil moisture readings were offloaded roughly once a month from October 1999 to June 2001. The reflectometers provide a means to monitor the redistribution of soil moisture following infiltration events and thus track the timing and movement of recharge pulses through the unsaturated zone [22-26].

Water Table Fluctuations

In the water level fluctuation method for recharge estimation [10, 13, 16, 27-43], a rise in the water table, in response to a precipitation-induced recharge event, is converted to an amount of recharge by multiplying the magnitude of the rise by the aquifer's specific yield. The method is attractive because water table measurements are often available, and the method is relatively quick, simple, and easily implemented. For this study, a water table well was installed at the conifer and the clear cut sites using an ATV – mounted geoprobe. Each well was outfitted with a 0 to 3 foot range Global Water Waterlogger that recorded hourly water table levels.

To analyze the water level data, the specific yield for each site was estimated from the reflectometer data (Fig. **2**). A reflectometer embedded in saturated sediment records the saturated moisture content, which equals the porosity. During the period of record, the near surface soil was saturated by a storm on July 8, 2000 and by the 2001 snowmelt event (Fig. **2**), providing two independent, reassuringly identical, estimates of porosity at each site: 0.30 for the clear cut site and 0.27 for the conifer site. The field capacity, the moisture content after gravity drainage has occurred, was measured at each site using the deep reflectometer, which lies below the root zone and is thus unaffected by transpiration, yielding values of 0.11 for the clear cut site and 0.07 for the conifer site. The difference between the porosity and the field capacity is the specific yield (Fig. **2**). The calculated values of specific yield of 0.19 for the clear cut site and 0.20 for the conifer site are typical for fine sands like those found at the sites [44, 45].

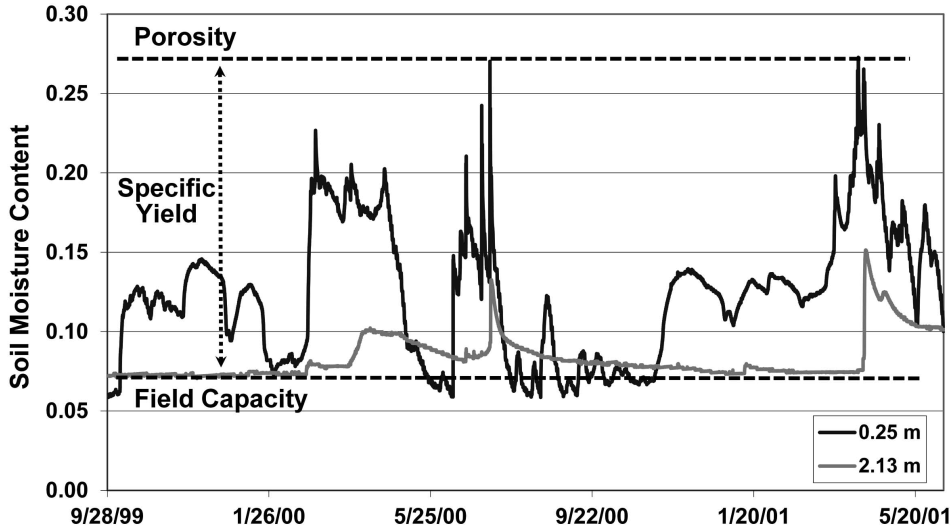

Fig. (2). Estimating specific yield from the reflectometer data. Shown here are the data for the conifer site.

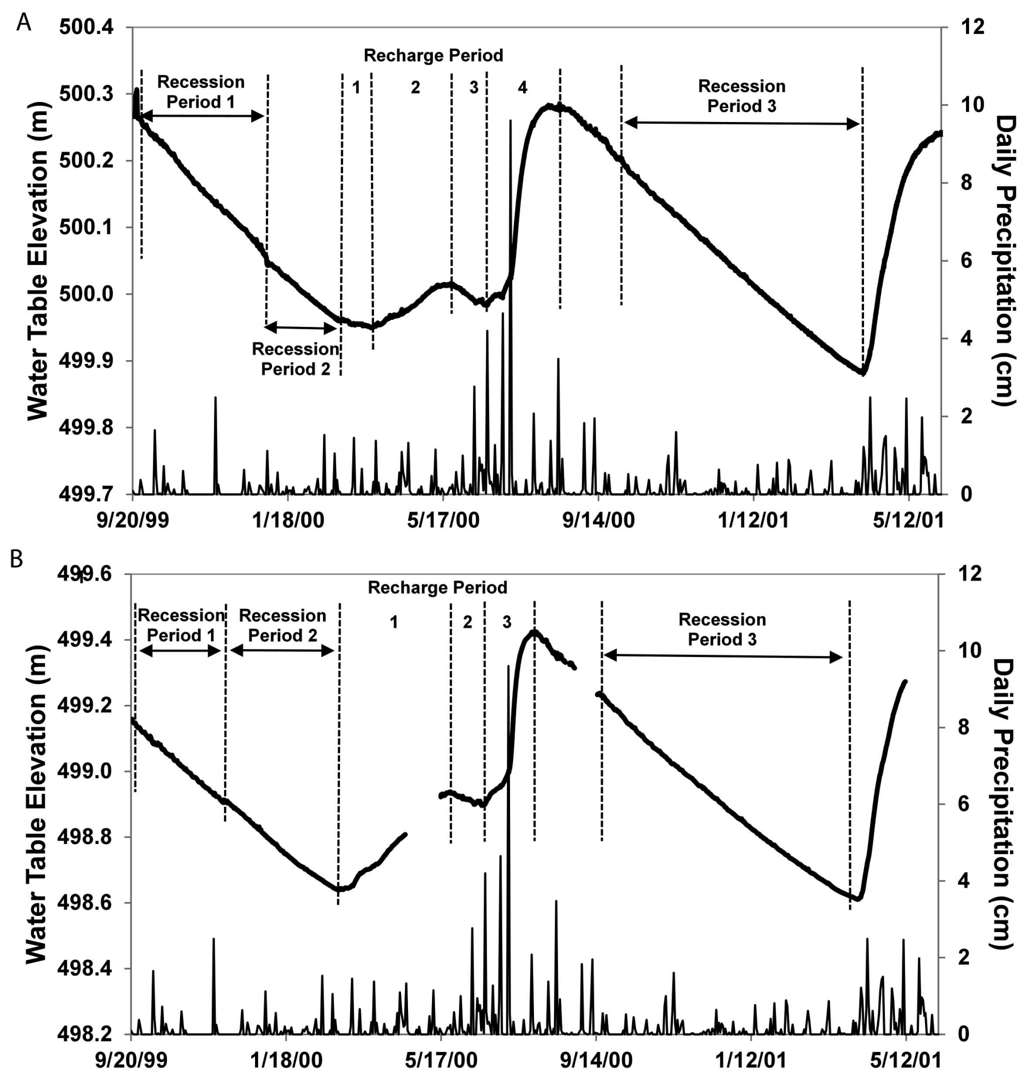

Fig. (3). Water table and precipitation data for the (**A**) conifer site and (**B**) clear cut site. The water level record is divided into periods of recharge and recession. Gaps in the water table record are due to equipment failure caused by tampering by wild animals.

Hourly water level records were analyzed using a water table fluctuation method as described by Johannson [31] to identify and quantify individual recharge events. The water level data were divided into periods of recharge and recession (extended periods when recharge did not occur, typically during the winter months) (Fig. **3**). For each well re-

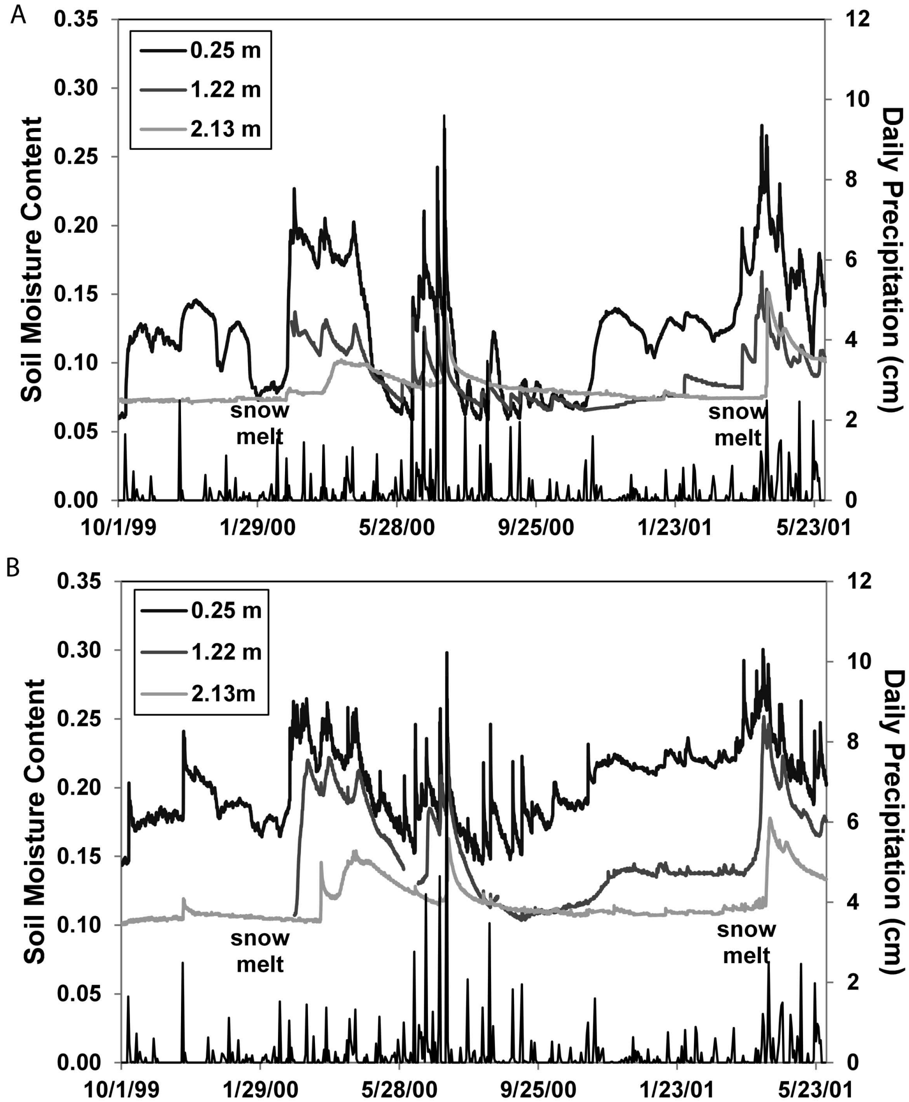

Fig. (4). Reflectometer and precipitation data for the (**A**) conifer site and the (**B**) clear cut site. Gaps in the reflectometer record are due to equipment failure caused by tampering by wild animals.

cord, a curve was fit to the water level data for each recession period. The shape of the curves for the three different recession periods was compared and essentially identical, and so the curve for recession period 3 was selected as the water table recession curve for that site (Fig. **3**). Starting at the beginning of each recharge period the water table recession curve was used to determine what the water table elevation would have been during the designated recharge periods if recharge had not occurred. The difference between the projected recession curve's water table elevation and the actual measured water table elevation at the end of each recharge period was then multiplied by the specific yield to determine the amount of recharge for each period.

The analysis of water table fluctuations is relatively straightforward, but the method requires that fluctuations in the water table are due solely to precipitation-induced recharge and that the downward flux of water through the unsaturated zone is greater than the lateral flux along the water table. At both sites, only natural processes affect the water table, and horizontal gradients are very small, on the order of 0.16%, as calculated from water table elevations measured in surrounding wells. As such, any significant and rapid rise in water level at the well is caused by the vertical flux of recharge from the unsaturated zone, which is further confirmed by the fact that the timing of the water table responses in each of these wells is well correlated with the major rainfall events and the downward propagating pulses of soil moisture recorded by the reflectometers at each of the sites. Similarly, the hourly recording interval and high resolution of the datalogger (within 0.0003 m) adequately captured any changes in the water table elevation and showed that recharge pulses were not rapidly dissipated, often lasting days, weeks, and in some cases months (Fig. **3**).

RESULTS AND DISCUSSION

Temporal Variability in Recharge

The influence of vegetation on soil moisture and the recharge process is reflected in the distribution of soil moisture at the conifer site (Fig. **4A**). As water infiltrates, most is retained in the upper meter of soil where water is actively removed by evapotranspiration, causing the moisture content to drop below field capacity during the growing season. The

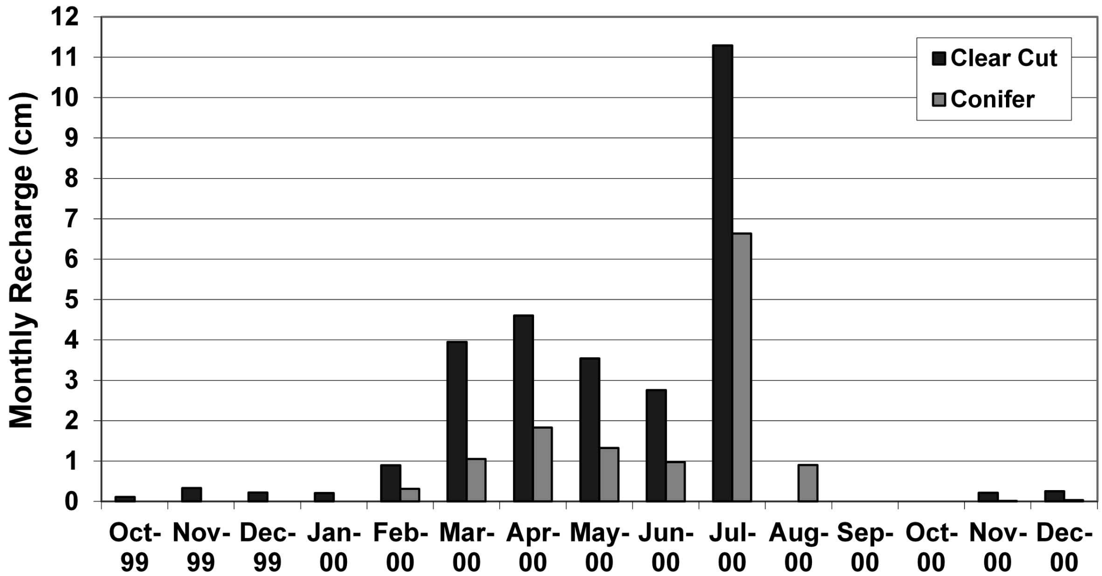

Fig. (5). Monthly recharge estimates as calculated from water table data (Fig. **3**) and estimates of specific yield (Fig. **2**) using the water level fluctuation method.

soil's moisture content must be brought back to field capacity before water can penetrate to the lowest reflectometer located below the root zone. Consequently, the volume of water moving down through the soil profile decreases and the size of the infiltrating pulse diminishes with depth (Fig. **4A**). In some instances, all of the infiltrating water is retained in the upper meter such that no water penetrates below the root zone (Fig. **4A**).

From late spring through early fall, the air temperatures are at their highest, the conifers are vigorously transpiring, and the soil moisture content in the root zone consequently, as measured by the shallow and middle reflectometers, reaches its lowest annual levels at the site (Fig. **4A**). Excluding brief periods of time immediately following rainfall events, the moisture content during the growing season typically increases with depth as the extent and density of root networks decrease. The 2000 data are atypical for this region as there were three major rainfall events in late June and early July that temporarily saturated the system; before and after these events, however, moisture contents at the conifer site followed the expected pattern of increasing moisture content with depth. From late fall through spring when vegetation was dormant, moisture content decreased with depth (Fig. **4A**). At the clear cut site, which was devoid of vegetation except for grasses, moisture content generally decreased with depth throughout the year (Fig. **4B**)

Individual recharge events as calculated by the water level fluctuation analysis were summed to give monthly recharge rates for the period October 1999 to December 2000 at the two sites (Fig. **5**). The water table responses (Fig. **3**) are well correlated with major rainfall events and the downward propagating pulses of soil moisture recorded by the reflectometers (Fig. **4**). The deep reflectometer data (Fig. **4**) and water level data (Fig. **3**) for the two sites show that recharge was limited to a few specific events during the period of study. Recharge occurred during the spring snowmelts of 2000 and 2001, select thunderstorms in March and April of 2000, and a series of major thunderstorms in late June and early July of 2000, during which over 25 cm of rain fell over a 3½ week period. Typically in this region, precipitation falls and accumulates as snow from November through March. The spring snowmelt constitutes the major recharge event of the year, often contributing in excess of 2/3 of the annual recharge [20]. Minor recharge is occasionally associated with spring and/or late fall rains when transpiration and interception are negligible and the ground is unfrozen. A major recharge event rarely occurs during the summer months when the foliage is full, transpiration is at a maximum, and soil moisture content is typically at a minimum, but 2000 was an anomalous year with a limited build up of snow and a small amount of recharge associated with the snowmelt and spring and fall rains and the largest recharge event of the year occurring in early July (Figs. **3** and **4**).

The timing of the snowmelt event and, to a lesser extent, the antecedent moisture content prior to onset of winter appear to be as important as the size of the snowpack in dictating the amount of snowmelt recharge that occurs. Fall 1999 was the driest of the preceding ten years. Snowmelt occurred atypically early, in late February / early March compared to late March / early April when it normally occurs. Air temperatures anomalously rose to over 20 ℃ in late February, rapidly melting the snowpack while the ground was still frozen (Fig. **6**). Consequently, much of the meltwater was lost to runoff or evaporated at the surface. The 2000 melt was one of the few times true overland flow has ever been observed in this basin.

During the first week of March there was a temporary warming of the soil (Fig. **6**) that allowed some water to infiltrate (Fig. **4A**), but by that time, most of the snowmelt had already run off, and most of the water that did infiltrate was retained in the near surface where it replenished the moisture content of the soil, still dry from the preceding fall. There was essentially no response at the deep reflectometers (Fig. **4**) or the water table (Fig. **3**) at either site. The 2001 snowmelt response, which was significantly larger and is more typical for this region, yielded substantially more recharge than the 2000 melt, as reflected in the soil moisture response and water table rise at both sites (Figs. **3** and **4**).

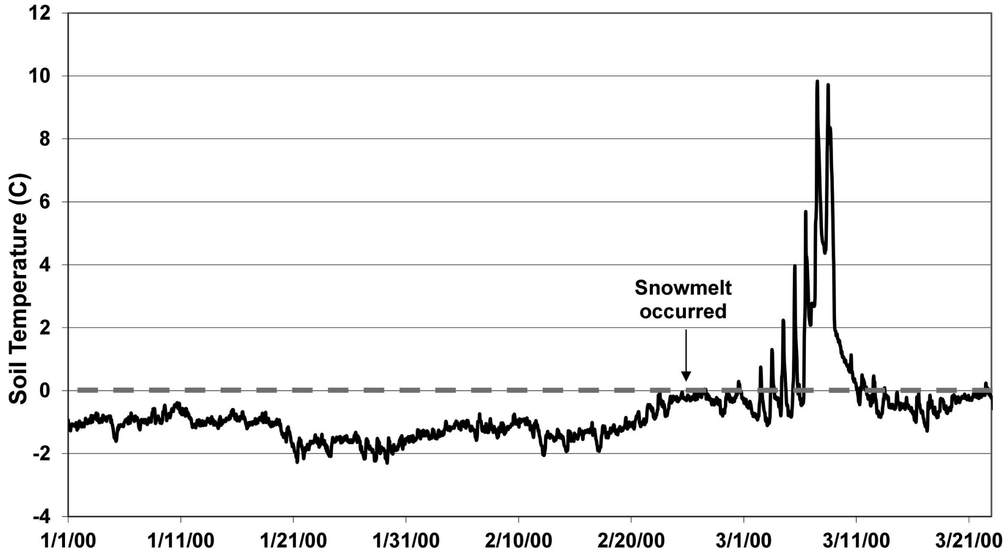

Fig. (6). Soil temperature measured at 5 cm depth at the conifer site in 2000. The freezing point is marked in the gray dashed line (0 ºC) and the timing of the snowmelt event is noted. When the snowmelt began in late February, the ground surface was still frozen, and thus, most of the meltwater ran off.

The significance and magnitude of the snowmelt event has important implications for water resource managers in the north central U.S., and presumably in other areas with large seasonal snowfall. The loss of most of the 2000 snowmelt to runoff potentially could have had deleterious impacts on aquatic ecosystems and wetlands had not the series of large storms in June and July generated significant recharge. Based on the observed seasonal recharge patterns for this region, a small, or early, snowmelt event is likely to yield a small net annual recharge for that year. In these years, water managers could preemptively plan for drought conditions well before a drought occurs in the event that large volumes of recharge do not occur during the summer and fall months to compensate for the snowmelt deficit.

Except for the snowmelt event, very few precipitation events generate recharge in this basin. There appears to be a minimum size storm required for recharge to occur. Regardless of the time of year, no storm of less than 1.25 cm of rainfall in a day generated a measurable response at either of the deep reflectometers (Fig. **3**) or at the water table (Fig. **4**). Although the 2000 snowmelt generated limited recharge, it wetted the soil column, allowing for a few small recharge events in late winter / early spring. In March (3/9/00 and 3/26/00) and April (4/20/00), 1.37 and 1.32 cm rain storms, respectively, yielded measurable recharge, reflected by the intermittent pulses in the deep reflectometer records (Fig. **4**) and water table responses (Fig. **3**). At these times the soil was close to field capacity from snowmelt and vegetation was dormant such that these relatively smaller precipitation events generated recharge. Starting in late spring when moisture is continually removed by transpiration, it typically takes larger individual rainfall events (> 2 cm) or elevated soil moisture levels prior to smaller rainfall events (>1.25 cm) to penetrate deep in the soil and produce a rise in the water table.

The size of the recharge event is a function of both the magnitude of precipitation and the amount of antecedent moisture in the soil prior to the storm [46]. Not surprisingly, the largest rainfall events (> 4 cm) (6/20/00, 7/2/00, and 7/8/00) generated the largest recharge responses (Figs. **3** and **4**). Antecedent moisture, however, is also important, particularly for determining if the smaller, yet still sizable, precipitation events (1.25 – 4 cm) generate recharge. Its significance was particularly evident at the conifer site where many large storms (> 2 cm) (11/23/99, 6/10/00, 7/26/00, 8/14/00) that generated little to no response at the deep reflectometer (Fig. **4**) occurred when antecedent moisture levels were low due to a combination of limited rainfall in the weeks prior to the storm and the continual removal of water by transpiration.

Spatial Variability in Recharge

The timing and relative intra-annual distribution in recharge (Fig. **5**) at the clear cut and conifer sites are in reasonable agreement and aligned with the annual snowmelt and major rainfall events (Figs. **3** and **4**), but the magnitude of recharge varies markedly between the two sites (Fig. **5**) owing to differences in vegetation, which influence the amount of interception and transpiration, both of which affect recharge. The lack of extensive vegetation at the clear cut site allowed the soil to remain at or close to field capacity, and consequently, most infiltration traveled rapidly through the unsaturated zone. As a result, the clear cut site had approximately twice the recharge rate as the conifer site (Fig. **5**). If one assumes that the recharge rate at the clear cut site prior to cutting was similar to the conifer site, which has comparable sediments [20], clear cutting has caused a significant increase in recharge. This result supports findings by previous workers [35, 47-51] that clear cutting causes an increase in recharge rate.

The depth to the water table is ~3.9 meters at the clear cut site, compared to ~6.6 meters at the conifer site, and thus, the recharge pulse arrives more quickly at the clear cut site. For example, for the July 8th recharge event, the majority of the precipitation (~ 6cm) fell between 2 – 4am on July 8th. The water table at the clear cut site began to rise at 11pm that evening, but the conifer site water table did not respond until 8am the next morning. For both sites the water table responses are quite rapid due to the permeable nature of the sands that cover the region. The size of the lag between the infiltration event and the associated recharge response at the water table will obviously increase with increasing thickness of the unsaturated zone. Although the bulk of the basin has shallow water tables (<7 meters), Hunt *et al*. [52] found lags as much as months in other portions of the basin where the thickness of the unsaturated zone is significantly greater (15 - 25 meters thick).

CONCLUSIONS

Monitoring soil moisture content at multiple depths in the unsaturated zone with time domain reflectometry together with fluctuations in the water table using pressure transducers provides a means to identify and quantify recharge events. Collectively the two field techniques allow for a better understanding of the compounding and often countering factors (e.g., rainfall timing, intensity, and quantity, snowmelt, soil moisture conditions, properties of the soil and sediment, types of vegetation present, ground temperature) that control the recharge process. Independently, each approach has limitations, but collectively the two datasets provide a powerful way to track recharge through the unsaturated zone to the water table.

Recharge, as measured at two sites (a clear cut site and a conifer site) in the Trout Lake basin in northern Wisconsin, occurred during a few specific events during the period October 1999 to June 2001. In 2000, significant recharge was produced by spring snowmelt and select thunderstorms in March and April, as well as a series of major summer thunderstorms in late June and early July. Typically, the spring snowmelt is the biggest recharge event of the year, but 2000 was anomalous with the largest recharge event occurring during the summer when the foliage was full, transpiration was at a maximum, and soil moisture was low.

Recharge may be crudely correlated with rainfall, with the larger rainfall events yielding more recharge, but perhaps as important as the amount of rain that falls in a storm is the antecedent soil moisture prior to a major rainfall event. If a storm is preceded by weeks of wet weather, it is much more likely to generate recharge than if the prior weeks have been dry. Some storms of more than 2 cm of rain generated no measurable recharge at the conifer site because of low antecedent moisture, but in some instance smaller storms with a little more than half that amount yielded a water table response because preceding storms had replenished the soil's moisture capacity. Regardless, 1.25 cm of rainfall appears to be the minimum daily precipitation necessary to generate recharge in this basin as no storms less than this amount resulted in any measurable change in the moisture content or water table at depth.

The magnitude of a recharge event and the lag time between a precipitation event and the arrival of any corresponding recharge at the water table are a function of the thickness of the unsaturated zone, the soil, and the vegetation. The clear cut site has the shallower water table and the least extensive vegetative cover of the two sites and showed the faster and larger recharge response for each infiltration event. The results highlight the potential impacts of land cover change on the recharge process as clear cutting resulted in a two-fold increase in recharge rate.

Intra-annual fluctuations in recharge are significant in the study basin and are likely significant in other watersheds. Spatial variability in recharge caused by differences in vegetation cover is also significant in this basin. Collectively, temporal and spatial variability in recharge will be important for water resource management, flow modeling, and ecological analyses.

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